CPV in Charmed Baryons: Theoretical Aspects

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Workshop on singly and doubly charmed baryons
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Outline

1. Introduction

2. CPV in singly Cabibbo-suppressed modes

3. CPV in Cabibbo-favored modes

4. Summary

1. Introduction

- CP Violation (CPV) is established neither in charm nor in baryon
- **CPV in charm** decays plays an important role in searching for new physics (NP)
  - **SM** predictions are always **very small**
  - Any large CPV would clearly signal NP
  - especially for **NP** with **special up sector**
- **Searching for CPV is one of the most important topics in charm physics.**

1. Introduction

- **CPV in baryons**:
  - ➡ directly related to the baryogenesis, huge asymmetry in matter v.s. antimatter in Universe
- **CPV in charmed baryons**:
  - ➡ being measured by LHCb - large data set

$$A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\,\%$$

LHCb, 17; See A. Pearce's talk

1. Introduction

- Direct CPV in charm occurs in two cases:

SCS

tree + **penguin**

$V_{cd}V_{ud}/V_{cs}V_{us}$ + $V_{cb}V_{ub}$

λ $\lambda^5 + i\lambda^5$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta a_{CP}^{\rm dir} = (-0.061 \pm 0.076)\%$$

LHCb, 16

CF with K_S^0

CF + **DCS**

$V_{cs}V_{ud}$ + $V_{cd}V_{us}$

1 $\lambda^2 + i\lambda^6$

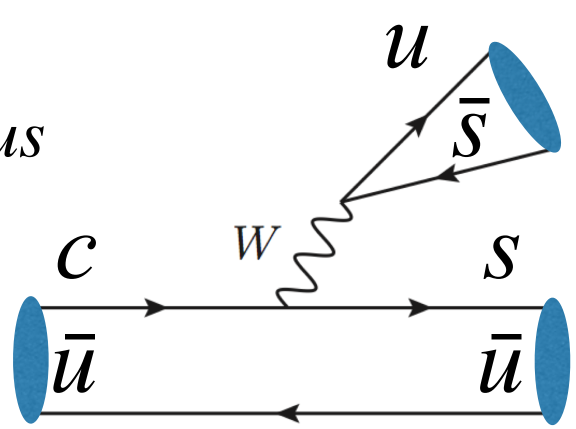
$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$

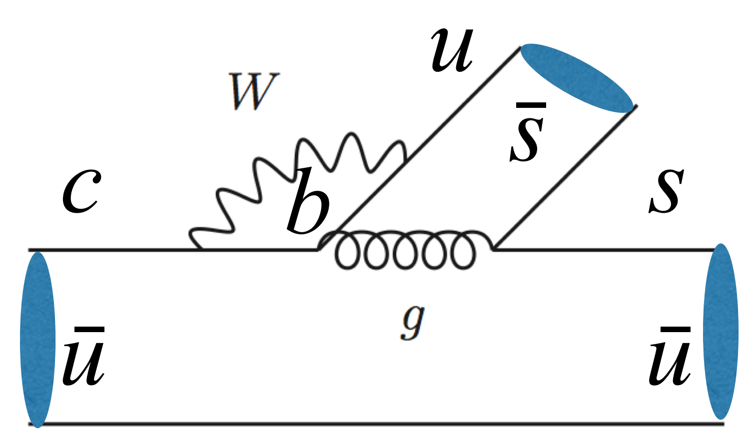
Belle, 12

2. Singly Cabibbo-Suppressed processes

- **Charmed Meson:** $D^0 \to K^+K^-$ $v.s.$ $D^0 \to \pi^+\pi^-$

$V_{cs}V_{us}$

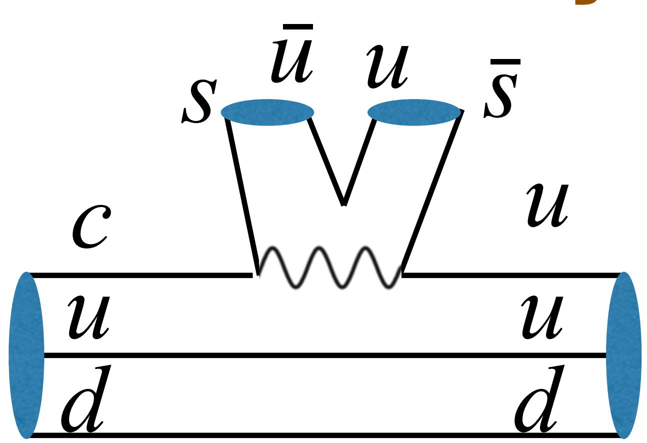


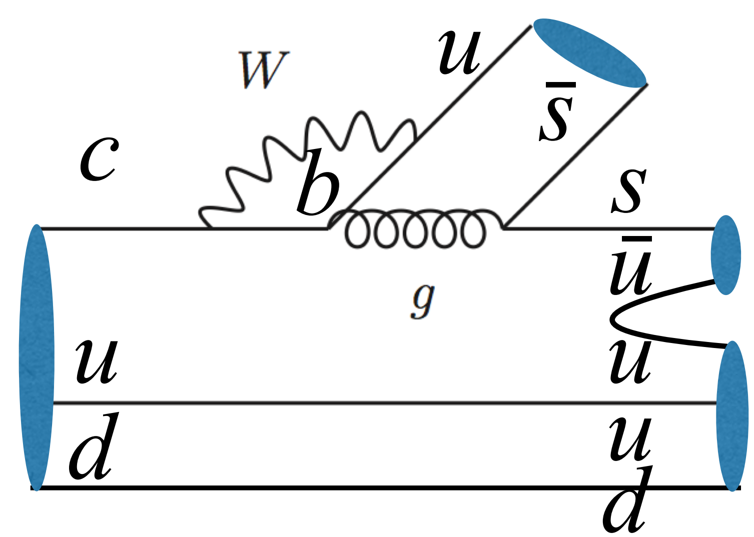


$V_{cb}V_{ub}$

- **Charmed Baryon:** $\Lambda_c^+ \to pK^+K^-$ $v.s.$ $\Lambda_c^+ \to p\pi^+\pi^-$

$V_{cs}V_{us}$

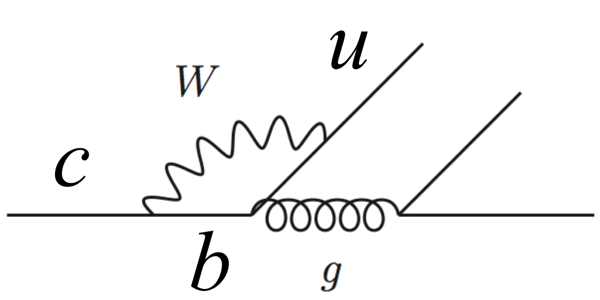




$V_{cb}V_{ub}$

Unknown Dynamics — Penguin

- m_c=**1.3GeV**, neither heavy nor light
  - heavy quark expansion $1/m_c$ does not work in exclusive processes
  - Dynamics is unknown by QCD



- **Ambiguity in penguins**

  $\Delta A_{CP}(K^+K^-, \pi^+\pi^-)$ predicted from **10^{-5}** to **10^{-2}**

Grossman, Kagan, Nir, 07; Bigi, Paul, 11; Isidori, Kamenik, Ligeti, Perez, 11; Brod, Grossmann, Kagan, Zupan, 11, 12; Bhattarcharya, Gronau, Rosner, 12; Feldmann, Nandi, Soni, 12; Cheng, Chiang, 12; Li, Lu, **FSY**, 12;

Unknown Dynamics — Tree

- Charm meson: tree amplitudes are extracted from data of branching fractions
  Cheng, Chiang, 10; Bhattarcharya, Rosner, 09;
  Li, Lu, Qin, **FSY**, 12, 14
- **Charm baryon: data is not sufficient to extract the full amplitudes**
  - Models are mostly done in 1990s. Recent works:
    - ⋆ SU(3) analysis — Lu, Wang, **FSY**, 16; Wang, Guo, Long, **FSY**, 17; Geng, Hsiao, Lin, Liu, 17, 18
    - ⋆ pole model — Kang, Cheng, Xu, 18

Impossible to reliably predict CPV in $\Lambda_c^+ \to pK^+K^-,\ p\pi^+\pi^-$

Suggest to probe CPV in $\Xi_c^+ \to pK^-\pi^+$

singly Cabibbo-suppressed, but widely used in experiment

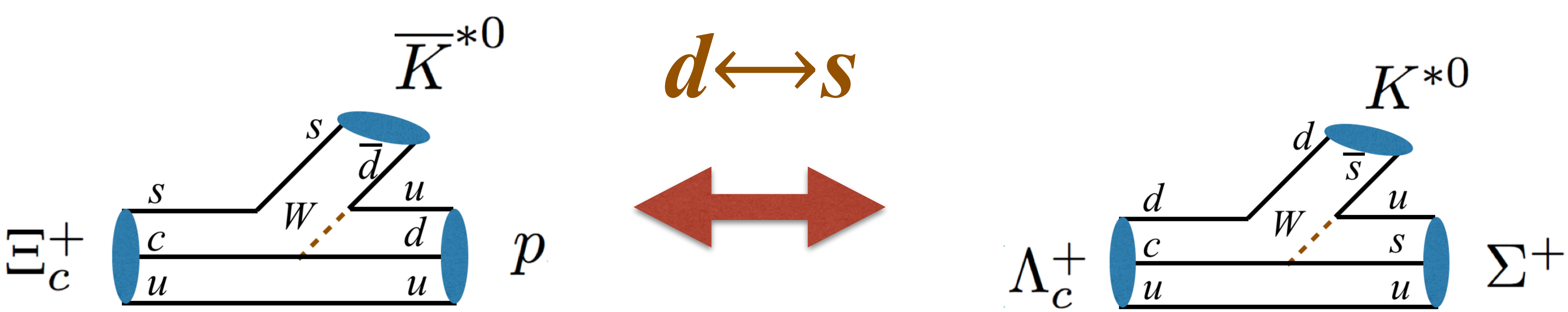
$$\Omega_c^* \to \Xi_c^+ K^- \qquad \Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

Branching fraction not measured, but predicted to be large

FSY, et ac, 1703.09086; Jiang, **FSY**, 1802.02948

Under U-spin symmetry, $d \leftrightarrow s$

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$



Suggest to probe CPV in $\Xi_c^+ \to pK^- \pi^+$

Under U-spin symmetry, $d \leftrightarrow s$

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$$

FOCUS, 01

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0}) / \mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

FOCUS, 02

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

FSY, et ac, 1703.09086; Jiang, **FSY**, 1802.02948

Suggest to probe CPV in $\Xi_c^+ \to pK^-\pi^+$

$$Br(\Lambda_c^+ \to pK^+K^-) \sim 0.15\,\%$$

$$\updownarrow$$

- Larger BR by one order

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

- Longer lifetime would benefit measurement at LHCb

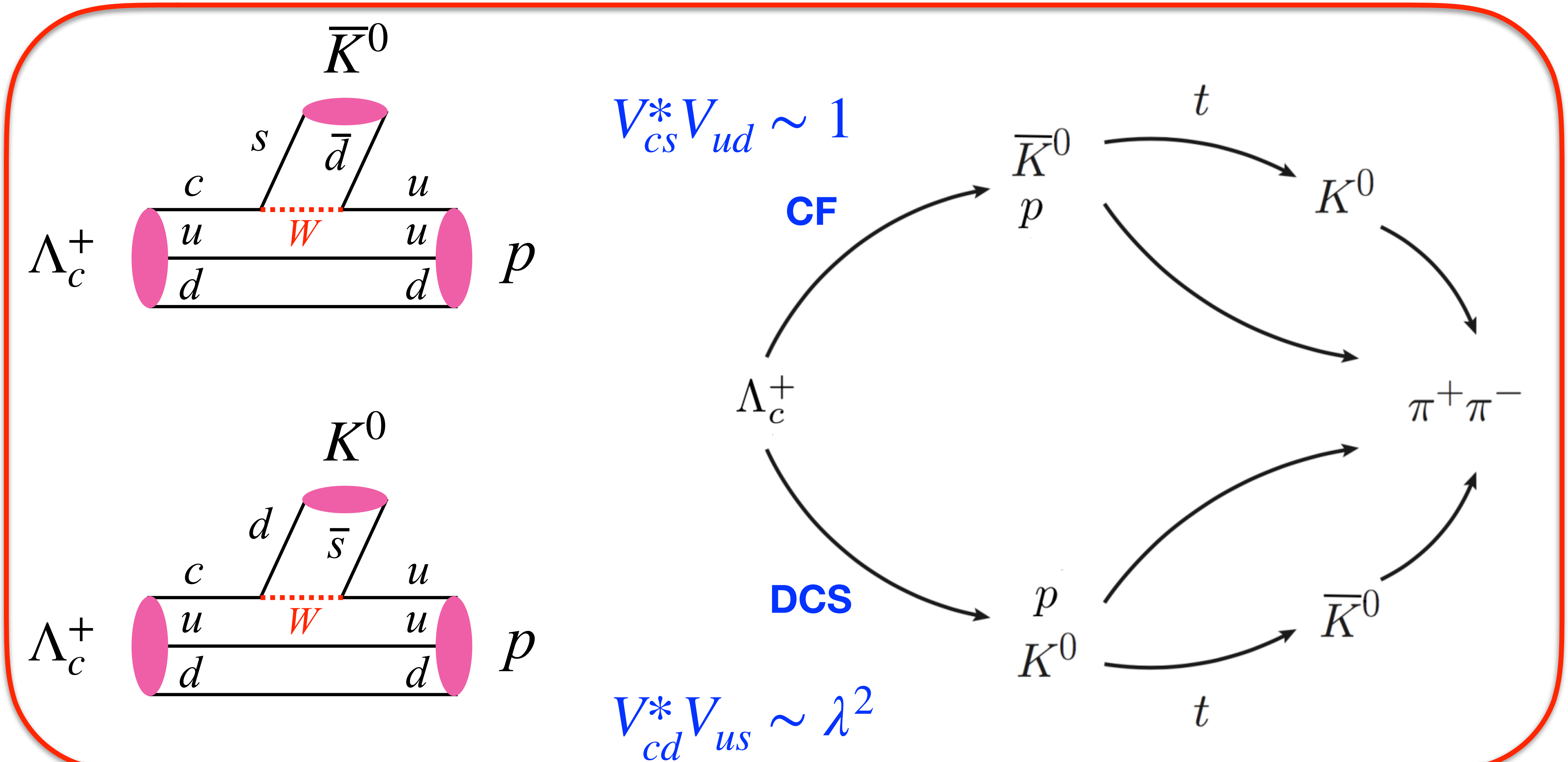
$$\tau(\Lambda_c^+) = (200 \pm 6) \times 10^{-15} s, \qquad \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} s,$$

Probably more data, even if suppressed by production.

Jia, **FSY**, in preparation

3. Cabibbo-Favored processes

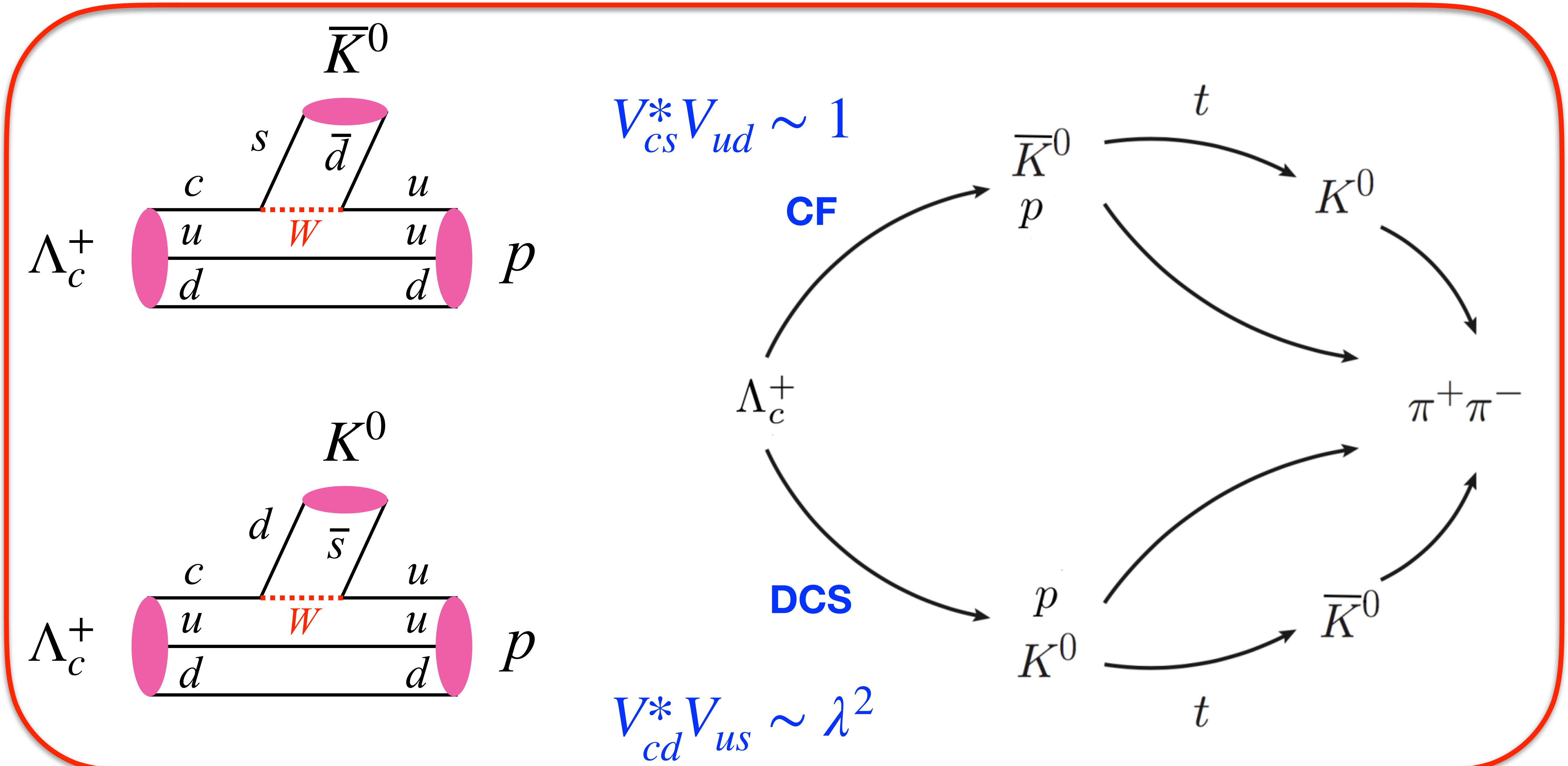
$\Lambda_c^+ \to p K_S^0 (\to \pi^+ \pi^-)$ Wang,Guo,Long,**FSY**,1709.09873



$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta})+A\lambda^5(\bar{\rho}-i\bar{\eta})/2 \\ -\lambda+A^2\lambda^5[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-A^2\lambda^4/2 \end{pmatrix}$$

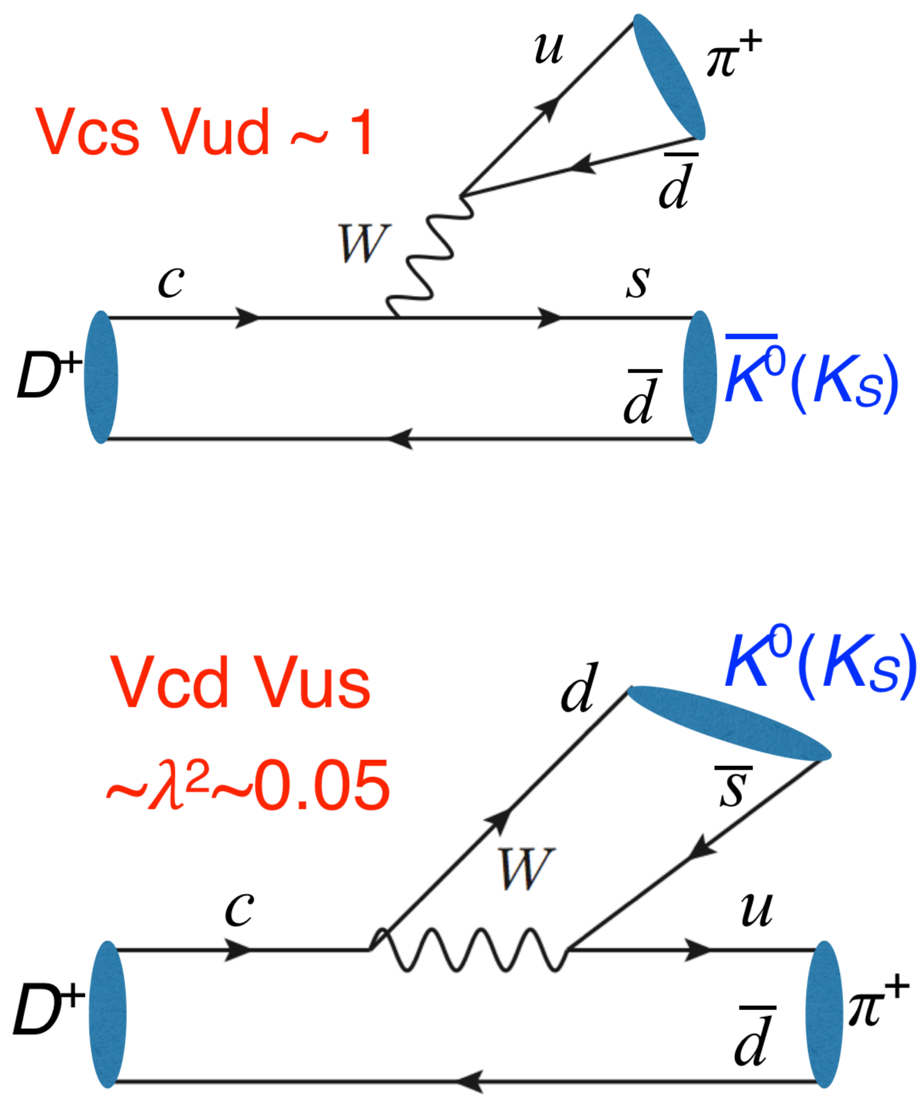
3. Cabibbo-Favored processes

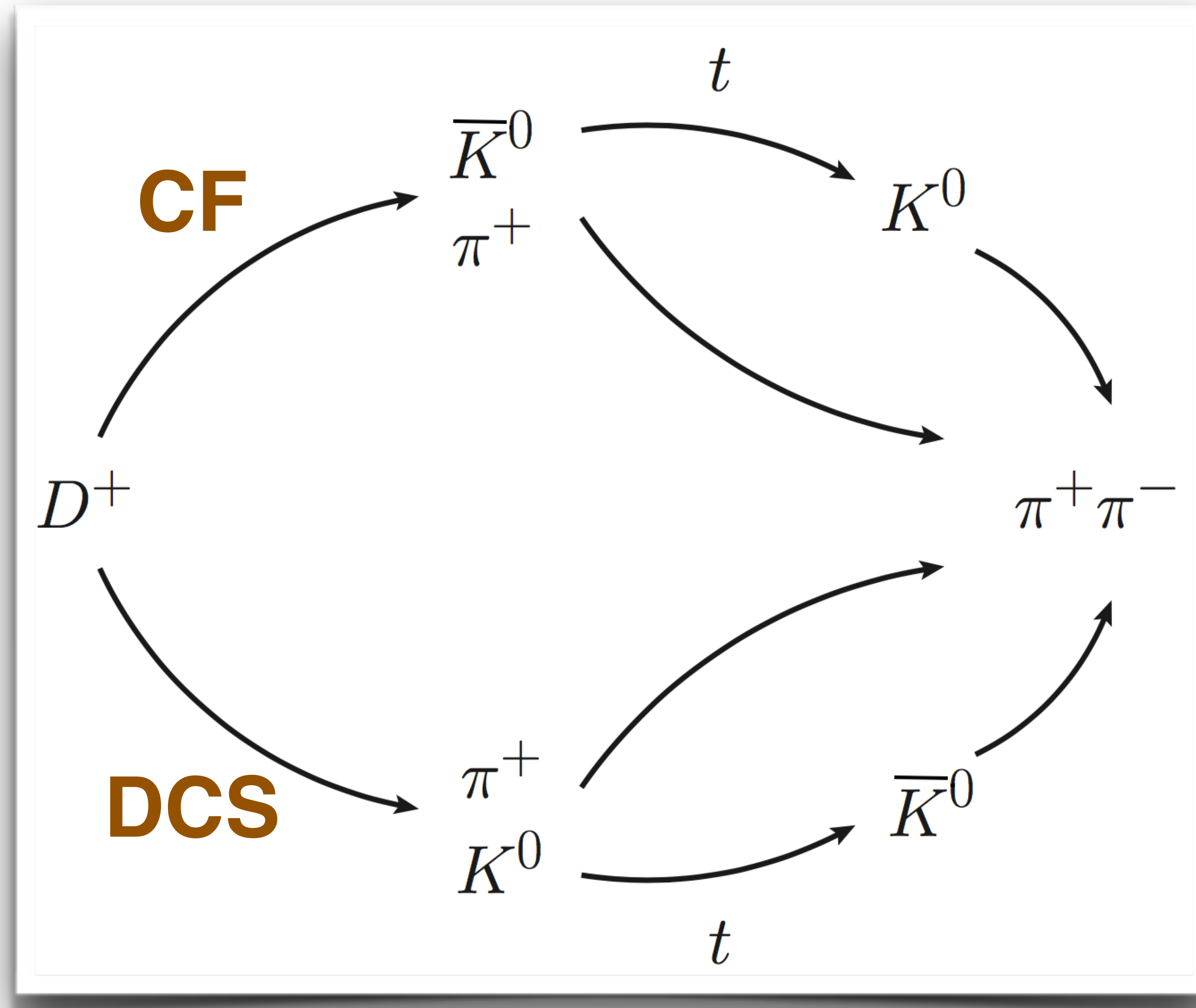
$\Lambda_c^+ \to pK_S^0(\to \pi^+\pi^-)$ Wang,Guo,Long,**FSY**,1709.09873



- **A new CPV effect exist in such processes**
- **The direct CPV is useful to search for new Physics**

Similar to $D^+ \to \pi^+ K_S$



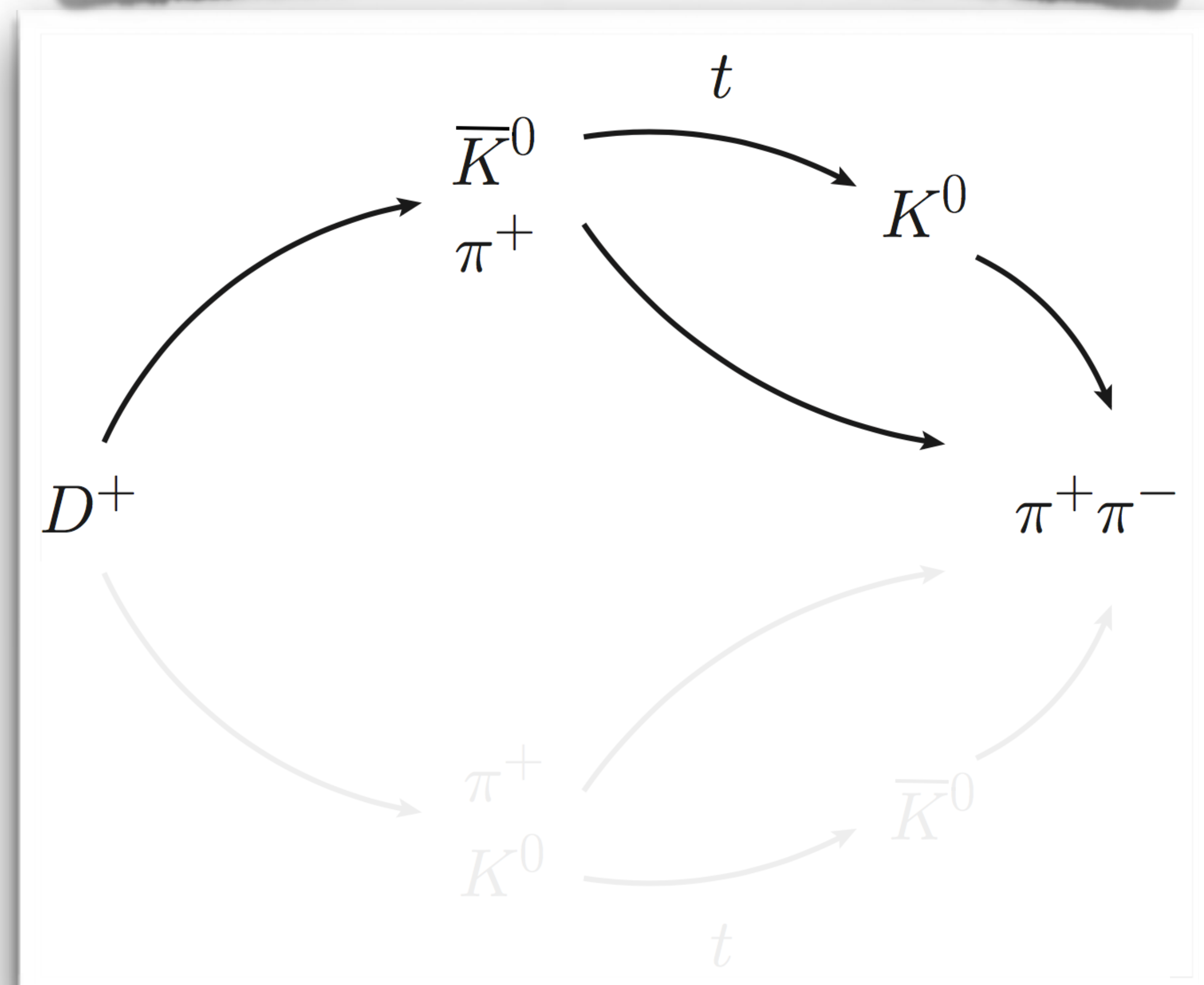


D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) \right] / D(t)$$

Indirect CPV in kaon mixing

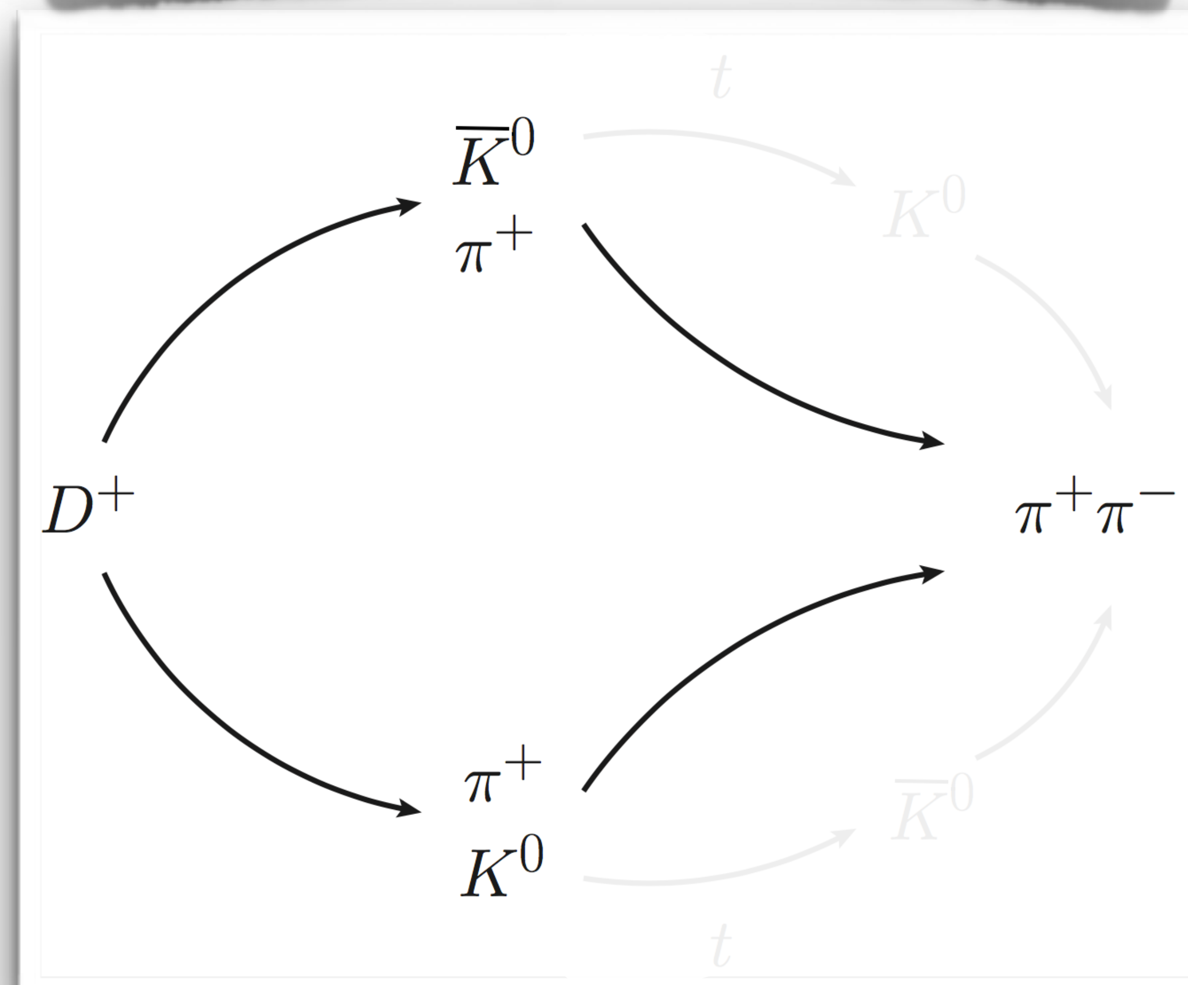
$\mathrm{Re}(\epsilon) = 10^{-3}$



Zhi-Zhong Xing, PLB 353, 313 (1995)

Direct CPV in charm decays

$\mathrm{Im}(V_{cd}V_{us}/V_{cs}V_{ud}) = \lambda^6 = 10^{-5}$



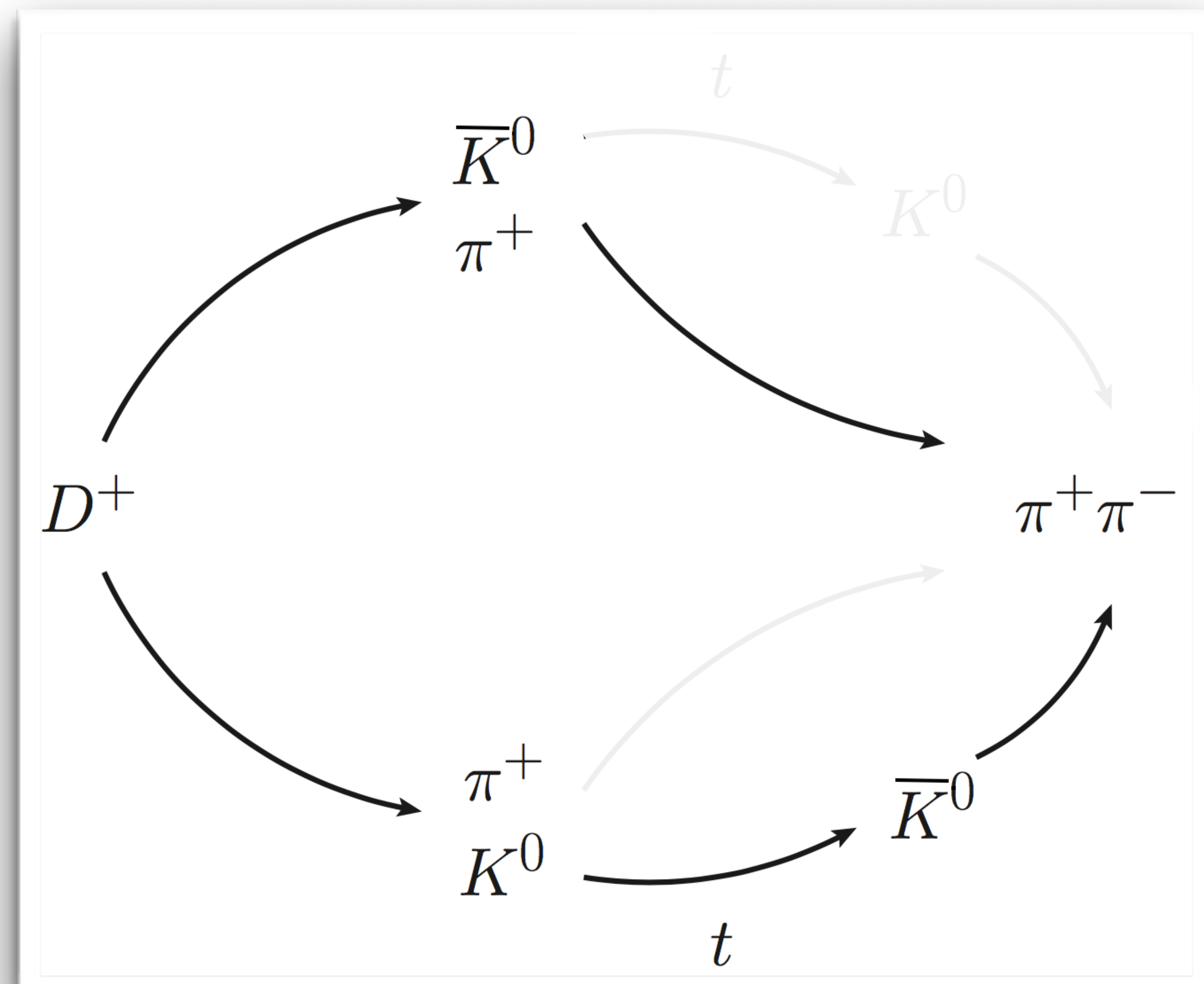
Bigi, Yamamoto, PLB 349, 363 (1995)

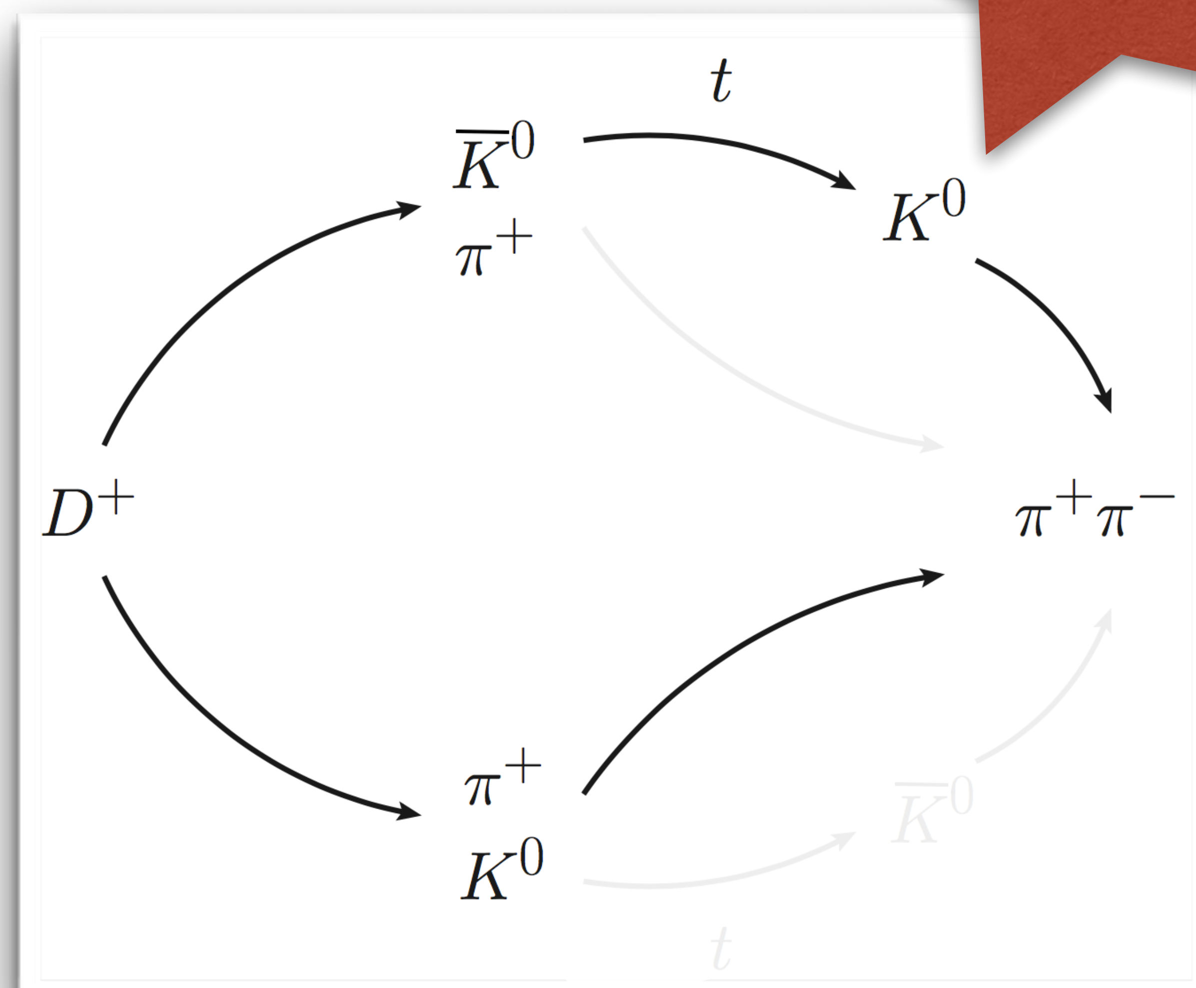
$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + \boxed{A_{CP}^{int}(t)} \right] / D(t)$$

CPV in interference between kaon mixing and charm decays

$\mathrm{Im}(\epsilon)\ \mathrm{Re}(V_{cd}^{*} V_{us} / V_{cs}^{*} V_{ud}) = 10^{-4 \sim -3}$

NEW





[D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)]

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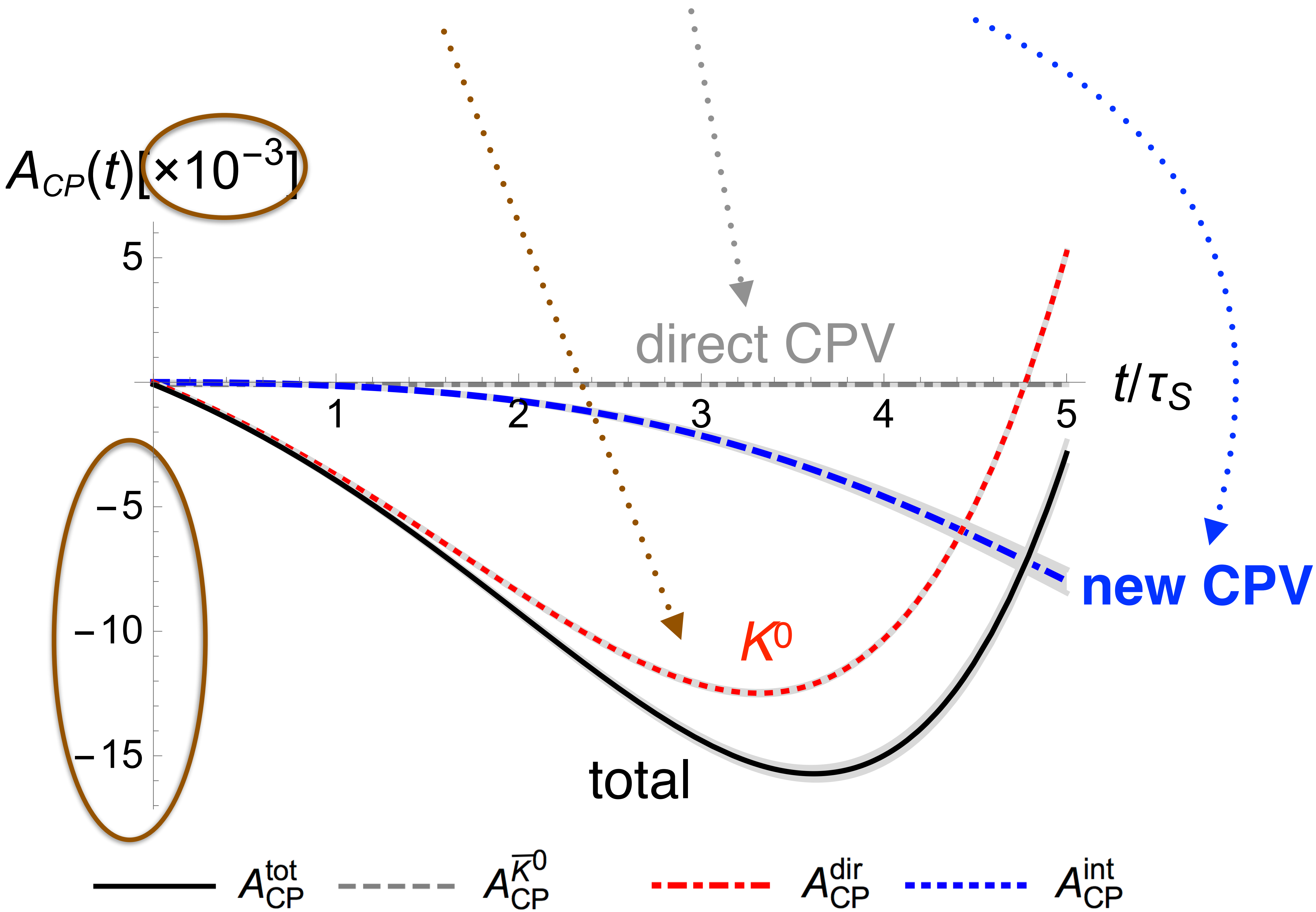

Belle: Evidence for CP Violation in the Decay $D^+ \to K_S^0 \pi^+$

PRL109,021601(2012) [arXiv:1203.6409]

$$A_{CP}^{D^+\to K_S^0\pi^+} \equiv \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^- \to K_S^0\pi^-)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^- \to K_S^0\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}, \quad (1)$$

$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$ Belle

$$A_{CP}^{\bar{K}^0} = (-0.339 \pm 0.007)\%$$

$$A_{CP}^{\Delta C} = (-0.024 \pm 0.115)\%$$

Belle, 12

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$$= A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0} + A_{CP}^{int}$$

$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$ Belle

$$A_{CP}^{\bar{K}^0} = (-0.339 \pm 0.007)\%$$

$$A_{CP}^{\Delta C} = (-0.024 \pm 0.115)\%$$

Belle, 12

$$A^{\Delta C} = (-0.006 \pm 0.115)\%$$

Wang, **FSY**, Li, 17

New CPV effect has to be considered

LHCb:

Search for CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$ decays

JHEP 1306 (2013) 112, [arXiv:1303.4906]

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\text{raw}}(D^+ \to \phi\pi^+) - A_{\text{raw}}(D^+ \to K_S^0\pi^+) + A_{CP}(K^0/\overline{K}^0)$$

SCS CF as a control mode

Direct CPV in $D^+ \to K_S^0\pi^+$ decay is assumed to be negligible.

BUT, $A_{CP}(D^+ \to \phi\pi^+) \leq \mathcal{O}(10^{-4})$ is expected

$A_{CP}^{\text{int}}(D^+ \to K_S^0\pi^+) \sim -0.4 \times 10^{-3}$ is comparable

New CPV effect is non-negligible!!!

Be careful when using $D \to \pi K_S$ as control mode, both at LHCb and Belle II

New Physics

in $D^+ \to \pi^+ K_S^0$, $\Lambda_c^+ \to p K_S^0$

direct CPV $$A_{CP}^{dir} \sim 2 r_f \sin\phi \sin\delta_f$$

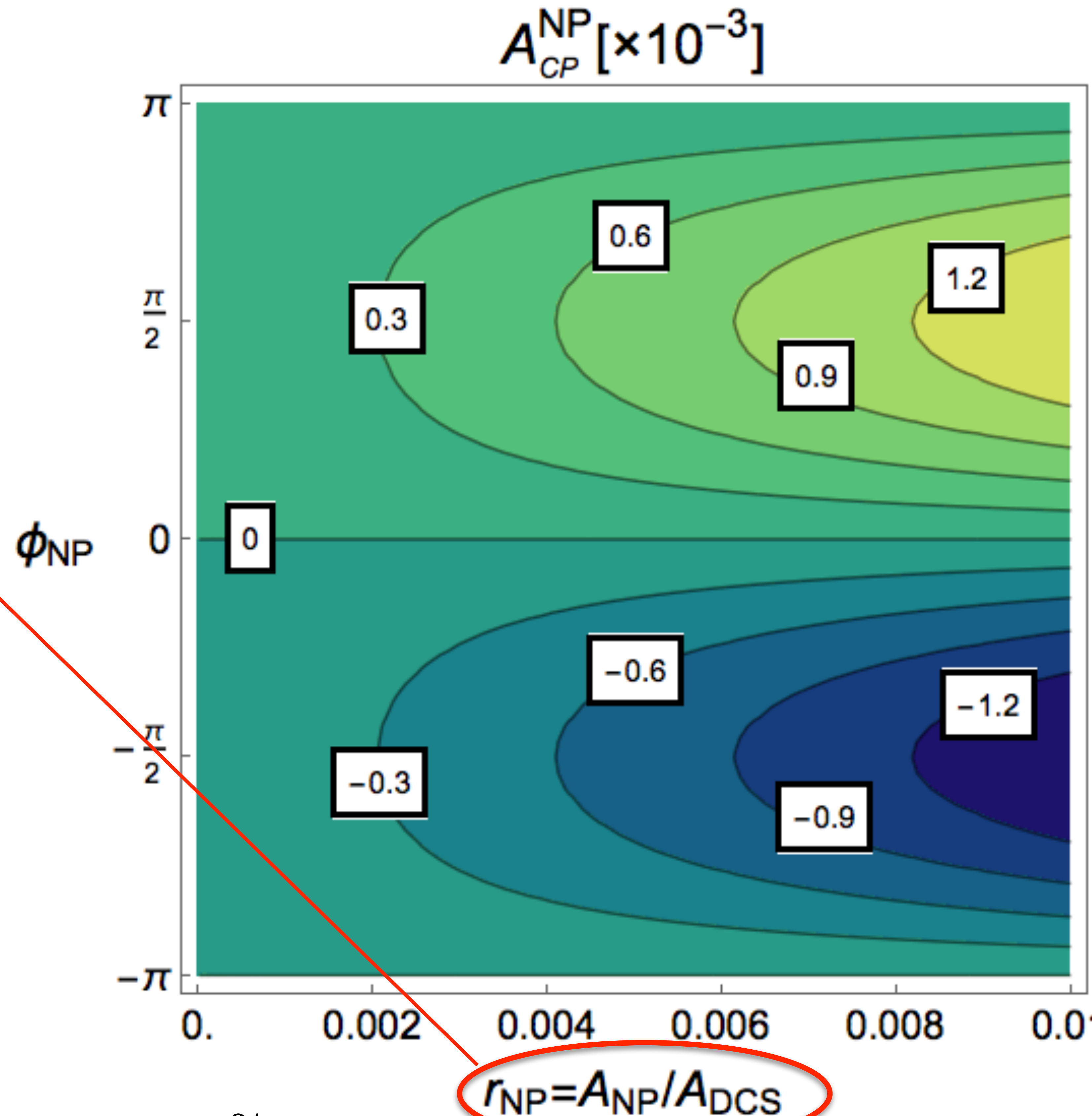
SM: $\phi \equiv Arg\,[-V_{cd}^* V_{us} / V_{cs}^* V_{ud}] = (-6.2 \pm 0.4) \times 10^{-4}$

NP: ϕ=O(1)

Search for new physics at tree-level

$$\mathcal{A}(D \to f K_S^0) = \mathcal{A}_{CF}^{\rm SM} + \mathcal{A}_{DCS}^{\rm SM}(1 + r^{\rm NP} e^{i\phi^{\rm NP}} e^{i\delta^{\rm NP}})$$

$$\frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} = (0.1 \sim 1)\%$$



$$\mathcal{A}(D \to f K_S^0) = \mathcal{A}_{CF}^{\rm SM} + \mathcal{A}_{DCS}^{\rm SM}(1 + r^{\rm NP} e^{i\phi^{\rm NP}} e^{i\delta^{\rm NP}})$$

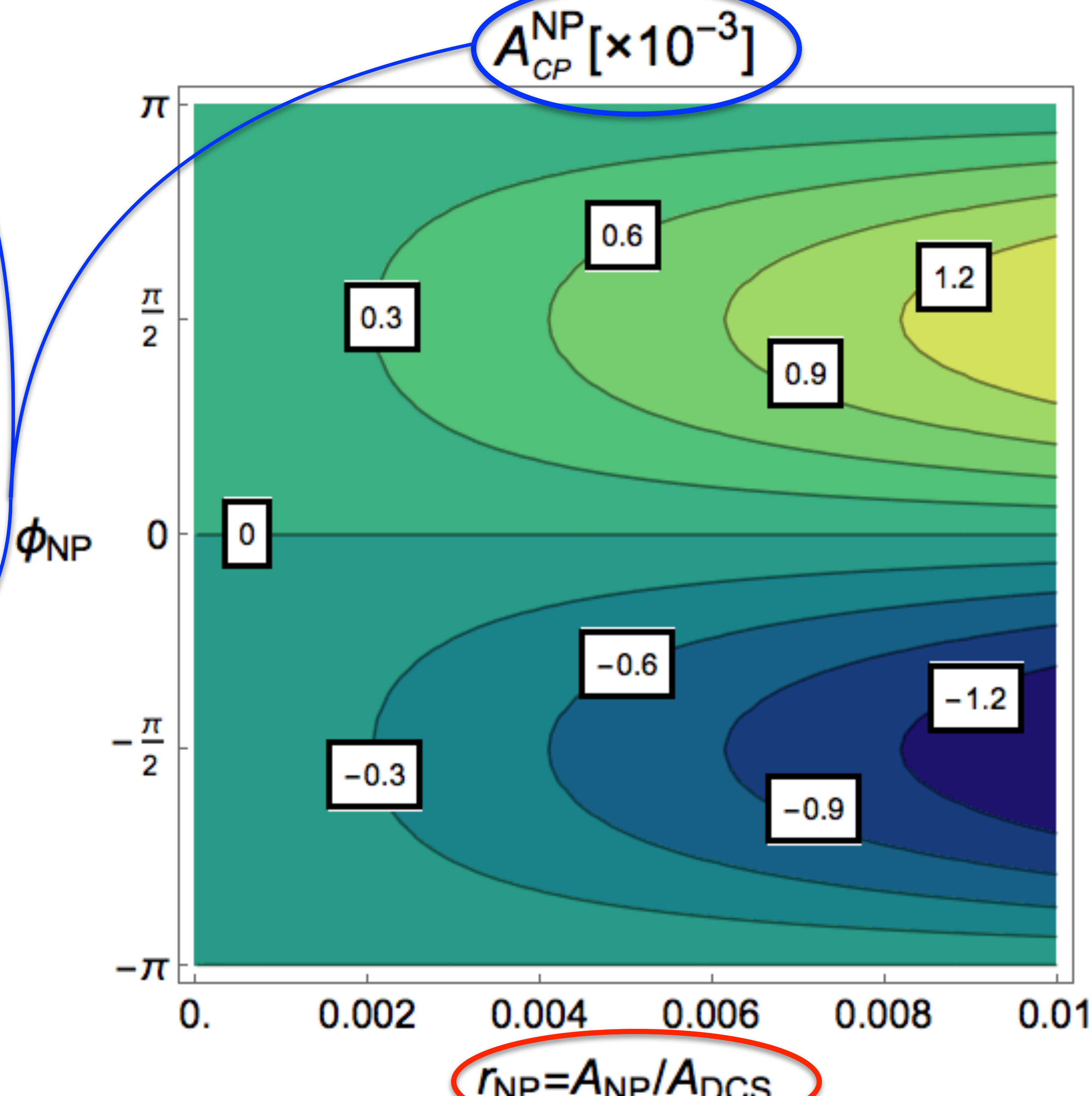
$A_{\rm SM}^{dir} = \mathcal{O}(10^{-5})$

Even if

$$\frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} = (0.1 \sim 1)\%$$

$$\frac{A_{CP}^{NP}}{A_{CP}^{SM}} = \mathcal{O}(10)$$

Promising for new physics!



Same game in charm baryon

Numerically, analyzed under SU(3) symmetry

$$c \to s u \bar{d} \qquad \overline{3} \times 3 \times \overline{3} = \overline{3} + \overline{3} + 6 + \overline{15}$$

$$\mathcal{O}_6 = \tfrac{1}{2}[(\bar{s}c)(\bar{u}d) - (\bar{u}c)(\bar{s}d)] \qquad \mathcal{O}_{\overline{15}} = \tfrac{1}{2}[(\bar{s}c)(\bar{u}d) + (\bar{u}c)(\bar{s}d)].$$

$$\mathcal{H}_{\text{eff}} = e\mathcal{H}^{ab}(6)T_{ac}\overline{\mathcal{B}}^c_d M^d_b + f\mathcal{H}^{ab}(6)T_{ac}M^c_d\overline{\mathcal{B}}^d_b + g\mathcal{H}^{ab}(6)\overline{\mathcal{B}}^c_a M^d_b T_{cd}$$

$$T_c = (\Xi^0_c, -\Xi^+_c, \Lambda^+_c), \qquad T_{ab} = \epsilon_{abc}T^c, \qquad \mathcal{H}^{22}(6) = 2 \qquad \mathcal{H}^{33}(6) = 2\tan^2\theta_C$$

$$\mathcal{B}^a_b = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{2/3}\Lambda \end{pmatrix} \qquad M^a_b = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\sqrt{2/3}\eta_8 \end{pmatrix}$$

Branching Fractions

$$e = 0.67 \pm 0.03, \quad |f| = 0.26 \pm 0.03, \quad h = f + g = (0.43 \pm 0.06)\ e^{i(0.97 \pm 0.06)} \qquad \chi^2/d.o.f = 0.17$$

Modes	Representation	$BR_{\rm exp}(\%)$	$BR_{\rm SU(3)}(\%)$
$\Lambda_c^+ \to \Lambda\pi^+$	$\frac{1}{\sqrt{6}}(-2e-2f-2g)$	1.30±0.07	1.30±0.17
$\Lambda_c^+ \to \Sigma^0\pi^+$	$\frac{1}{\sqrt{2}}(-2e+2f+2g)$	1.29±0.07	1.27±0.17
$\Lambda_c^+ \to \Sigma^+\pi^0$	$\frac{1}{\sqrt{2}}(2e-2f-2g)$	1.24±0.10	1.27±0.17
$\Lambda_c^+ \to pK_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) - \frac{1}{\sqrt{2}}(-2e)$	1.58±0.08	$1.36 \sim 1.80$
$\Lambda_c^+ \to pK_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) + \frac{1}{\sqrt{2}}(-2e)$		$1.24 \sim 1.67$
$\Lambda_c^+ \to \Xi^0K^+$	$-2f$	0.50±0.12	0.50±0.12
$\Xi_c^0 \to \Xi^-\pi^+$	$2e$		2.24±0.34
$\Xi_c^0 \to \Xi^0\pi^0$	$\frac{1}{\sqrt{2}}(-2e+2g)$		$0.07 \sim 1.81$
$\Xi_c^0 \to \Lambda K_S^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e+4f+4g) - \frac{1}{\sqrt{12}}(-4e+2f+2g)$		0.47±0.08
$\Xi_c^0 \to \Lambda K_L^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e+4f+4g) + \frac{1}{\sqrt{12}}(-4e+2f+2g)$		0.50±0.09
$\Xi_c^0 \to \Sigma^+K^-$	$2f$		0.31±0.09
$\Xi_c^0 \to \Sigma^0K_S^0$	$\frac{1}{2}\tan^2\theta_C(2e) - \frac{1}{2}(-2f-2g)$		0.23±0.07
$\Xi_c^0 \to \Sigma^0K_L^0$	$\frac{1}{2}\tan^2\theta_C(2e) + \frac{1}{2}(-2f-2g)$		0.20±0.06
$\Xi_c^+ \to \Xi^0\pi^+$	$-2g$		$0.01 \sim 10.22$
$\Xi_c^+ \to \Sigma^+K_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) - \frac{1}{\sqrt{2}}(2g)$		$0.06 \sim 4.84$
$\Xi_c^+ \to \Sigma^+K_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) + \frac{1}{\sqrt{2}}(2g)$		$0.00 \sim 4.30$

Wang,Guo,Long,**FSY**,1709.09873

CP Asymmetries

	$A_{CP}(\Lambda_c^+ \to pK_S^0)$	$A_{CP}(\Xi_c^0 \to \Lambda K_S^0)$	$A_{CP}(\Xi_c^0 \to \Sigma^0 K_S^0)$	$A_{CP}(\Xi_c^+ \to \Sigma^+ K_S^0)$
$S1$	$-3.15 \sim -2.67$	-3.13 ± 0.05	-3.42 ± 0.05	$-4.57 \sim -2.60$
$S2$	$-3.55 \sim -3.09$	-3.58 ± 0.04	-2.50 ± 0.10	$-2.91 \sim -1.39$

Wang,Guo,Long,**FSY**,1709.09873

Large ambiguity in prediction

But deserve to be payed more attention

More measurements on branching fractions are required

Summary

- CPV in charm baryon is important
- SCS processes:
  - ambiguity in theory,
  - suggestion to measure CPV in $\Xi_c{}^{+} \to pK^{-}\pi^{+}$
- CF processes:
  - new CPV effect has to be considered.
  - Direct CPV is promising to search for new physics.
- Measurements on branching fractions are very useful for theoretical analysis

Thank you very much!

$$D \to f K_S^0 (\to \pi^+ \pi^-)$$

$$A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)}$$

$$\Gamma_{\pi\pi}(t) \equiv \Gamma(D \to f K_S^0(t) \to f [\pi\pi]_K)$$

$$\overline{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\overline{D} \to \overline{f} K_S^0(t) \to \overline{f} [\pi\pi]_K)$$

$\frac{\text{DCS}}{\text{CF}}$

$$\frac{\mathcal{A}(D \to K^0 f)}{\mathcal{A}(D \to \overline{K}^0 f)} = r\, e^{i(\phi+\delta)}$$

δ → strong phase

ϕ → weak phase

r → $\sim\lambda^2 \sim 0.05$

$$A_{CP}^{\overline{K}^0}(t) = 2e^{-\Gamma_S t}\mathcal{R}e(\epsilon) - 2e^{-\Gamma t}\Big[\mathcal{R}e(\epsilon)\cos(\Delta m t) + \mathcal{I}m(\epsilon)\sin(\Delta m t)\Big],$$

$$A_{CP}^{\mathrm{dir}}(t) = e^{-\Gamma_S t}\, 2r_f \sin\delta_f \sin\phi$$

$$A_{CP}^{\mathrm{int}}(t) = -4r_f \cos\phi \sin\delta_f \Big[e^{-\Gamma_S t}\mathcal{I}m(\epsilon) - e^{-\Gamma t}\Big(\mathcal{I}m(\epsilon)\cos(\Delta m t) - \mathcal{R}e(\epsilon)\sin(\Delta m t)\Big)\Big]$$

$$\phi \equiv Arg\left[-V_{cd}^{*}V_{us}/V_{cs}^{*}V_{ud}\right] = (-6.2\pm0.4)\times 10^{-4}$$

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L)$$

$$\simeq \frac{-2\mathcal{I}m(\epsilon) + 2r_f \sin\delta_f \sin\phi - 4\mathcal{R}e(\epsilon) r_f \cos\phi \sin\delta_f}{1 - 2r_f \cos\phi \cos\delta_f}$$

CPV in kaon mixing — direct CPV — New CPV effect

(10^{-3}) — **(10^{-5})** — **($10^{-4\sim-3}$)**

Sensitive to New Physics CP phase

$$\Delta A_{CP}(D^+, D_s^+) \equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2)$$

$A_{CP}^{\overline{K}^0}$ is mode-independent and cancelled

In the limit of SU(3) symmetry

Topologies

$D^+ \to K_S^0\pi^+$ $\quad (1+\bar{\varepsilon}^*)V_{cd}^*V_{us}(C+A) - (1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}(T+C)$

DCS CF

$D_s^+ \to K_S^0K^+$ $\quad (1+\bar{\varepsilon}^*)V_{cd}^*V_{us}(T+C) - (1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}(C+A)$

DCS CF

Opposite sign of strong phases in the SU(3) symmetry

Constructive in $\Delta A_{CP}(D^+, D_s^+)$

Interesting modes in experiments

LHCb: $A_{CP}(D^+ \to K_S \pi^+) - A_{CP}(D_s^+ \to K_S K^+)$ **~10^-3**

$$= \left[A_{\rm raw}(D^+ \to K_S \pi^+) - A_{\rm raw}(D^+ \to K^- \pi^+ \pi^+)\right]_{Br=9\%}$$

$$- \left[A_{\rm raw}(D_s^+ \to K_S K^+) - A_{\rm raw}(D_s^+ \to K^- \pi^+ K^+)\right]_{Br=5\%}$$

and

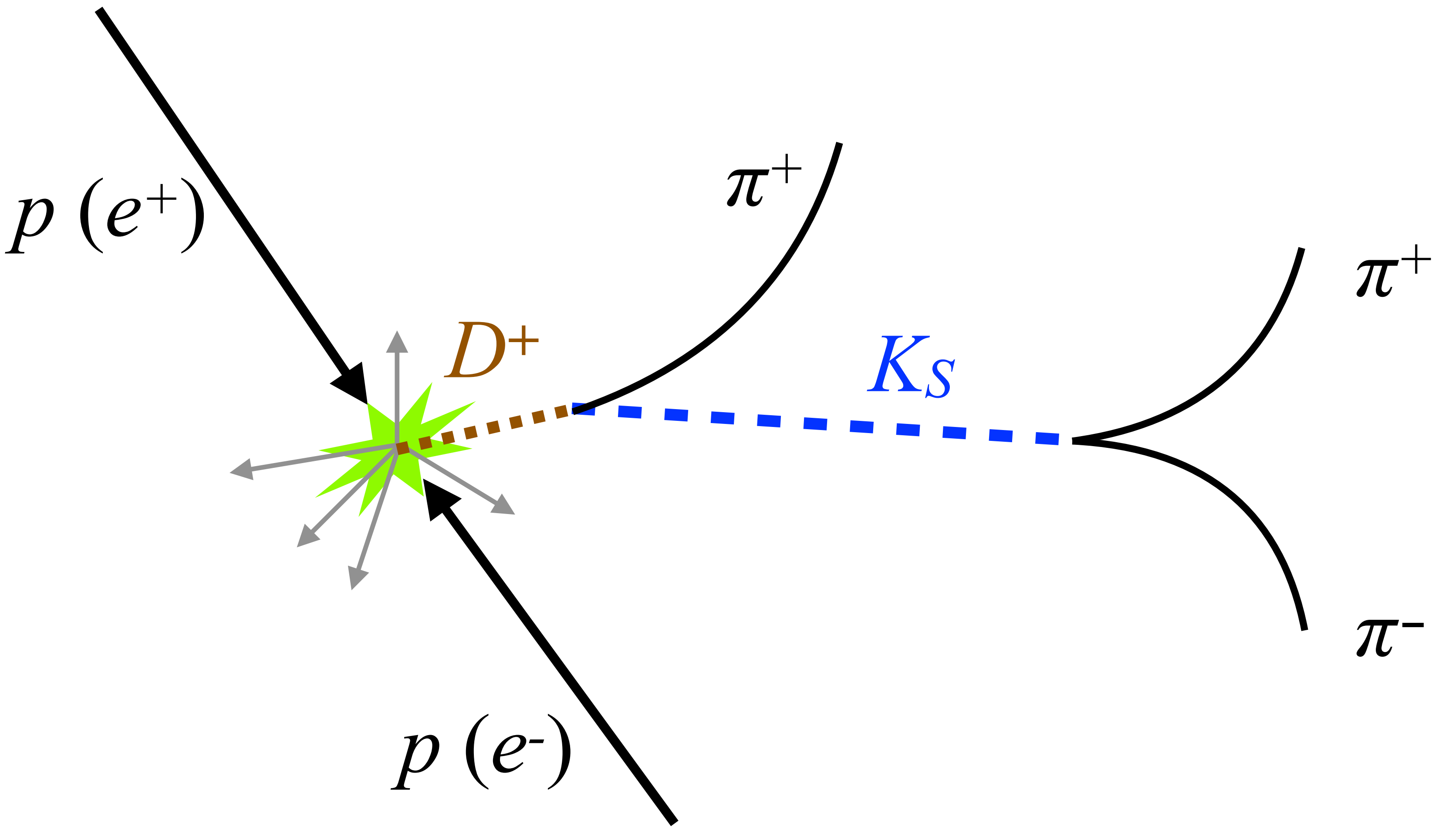
$$A_{CP}^{\Lambda_c^+ \to pK}(t_1, t_2) - A_{CP}^{D^+ \to K\pi^+}(t_1, t_2)$$

$$= [A_{raw}^{\Lambda_c^+ \to pK}(t_1, t_2) - A_{raw}^{\Lambda_c^+ \to pK^- \pi^+}]$$

$$- [A_{raw}^{D^+ \to K\pi^+}(t_1, t_2) - A_{raw}^{D^+ \to K^- \pi^+ \pi^+}]$$

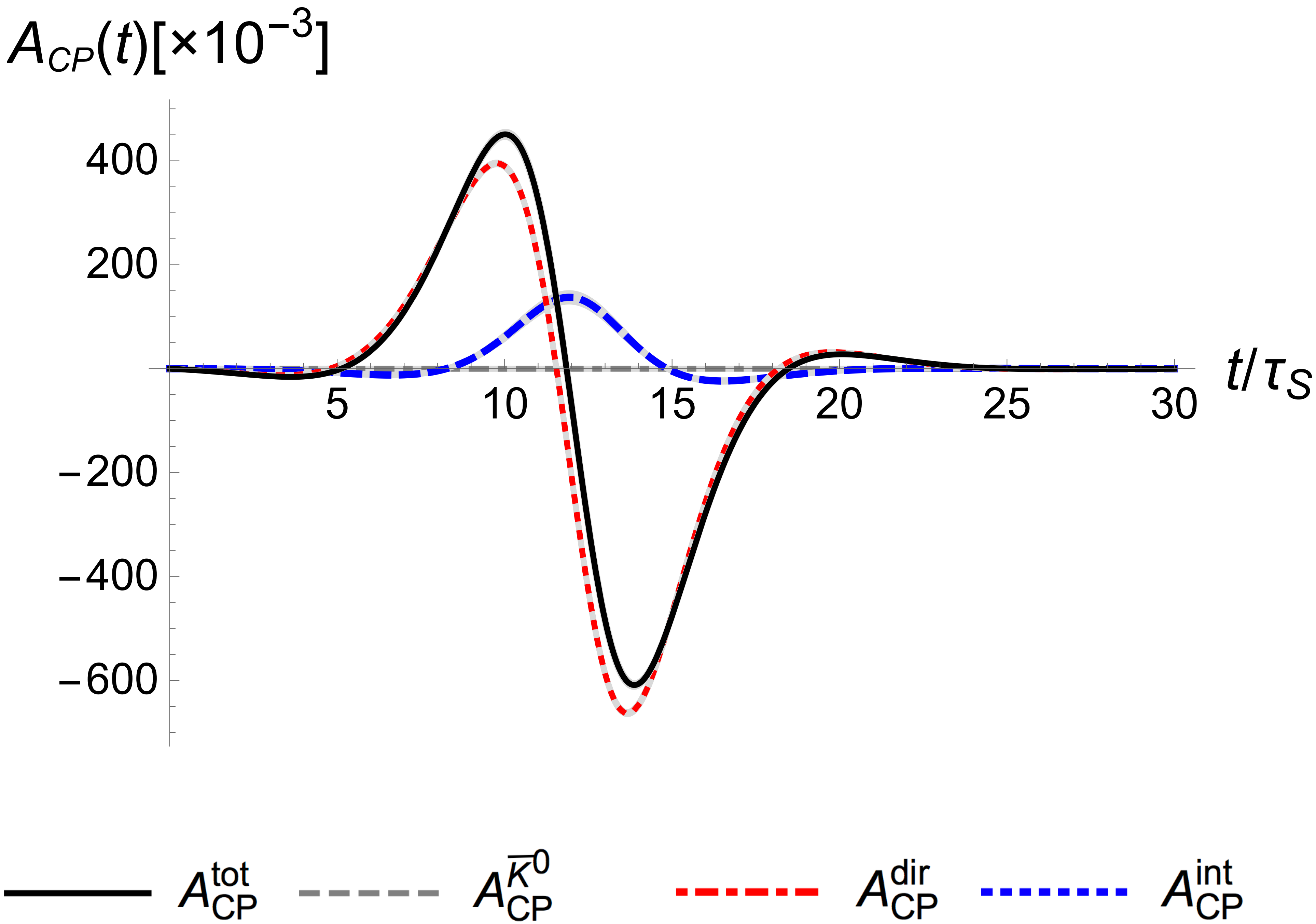
Time-dependent & Time integrated CPV

time of K_S flying



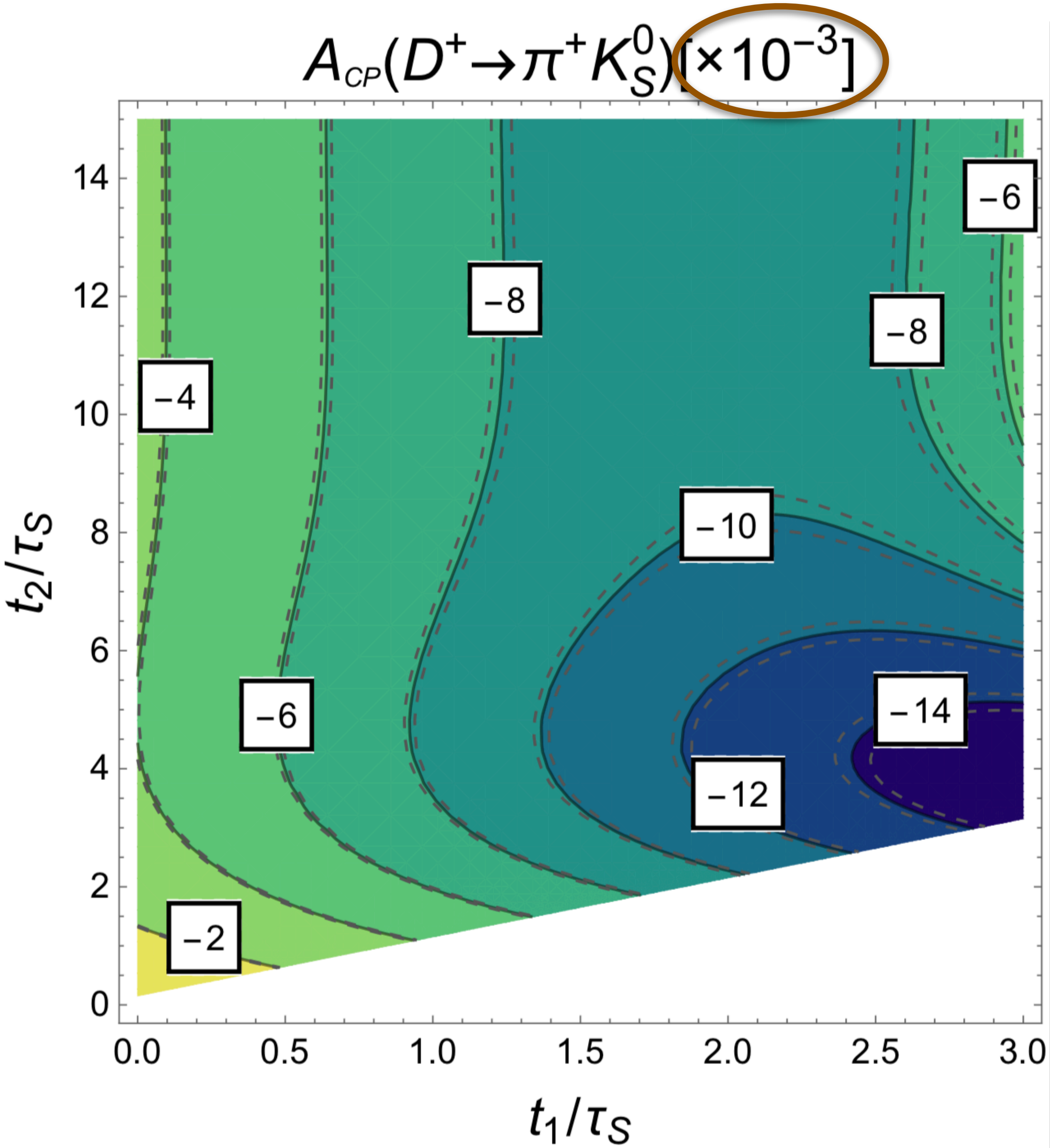
Time-dependent CPV

$$D^+ \to \pi^+ K_S^0$$

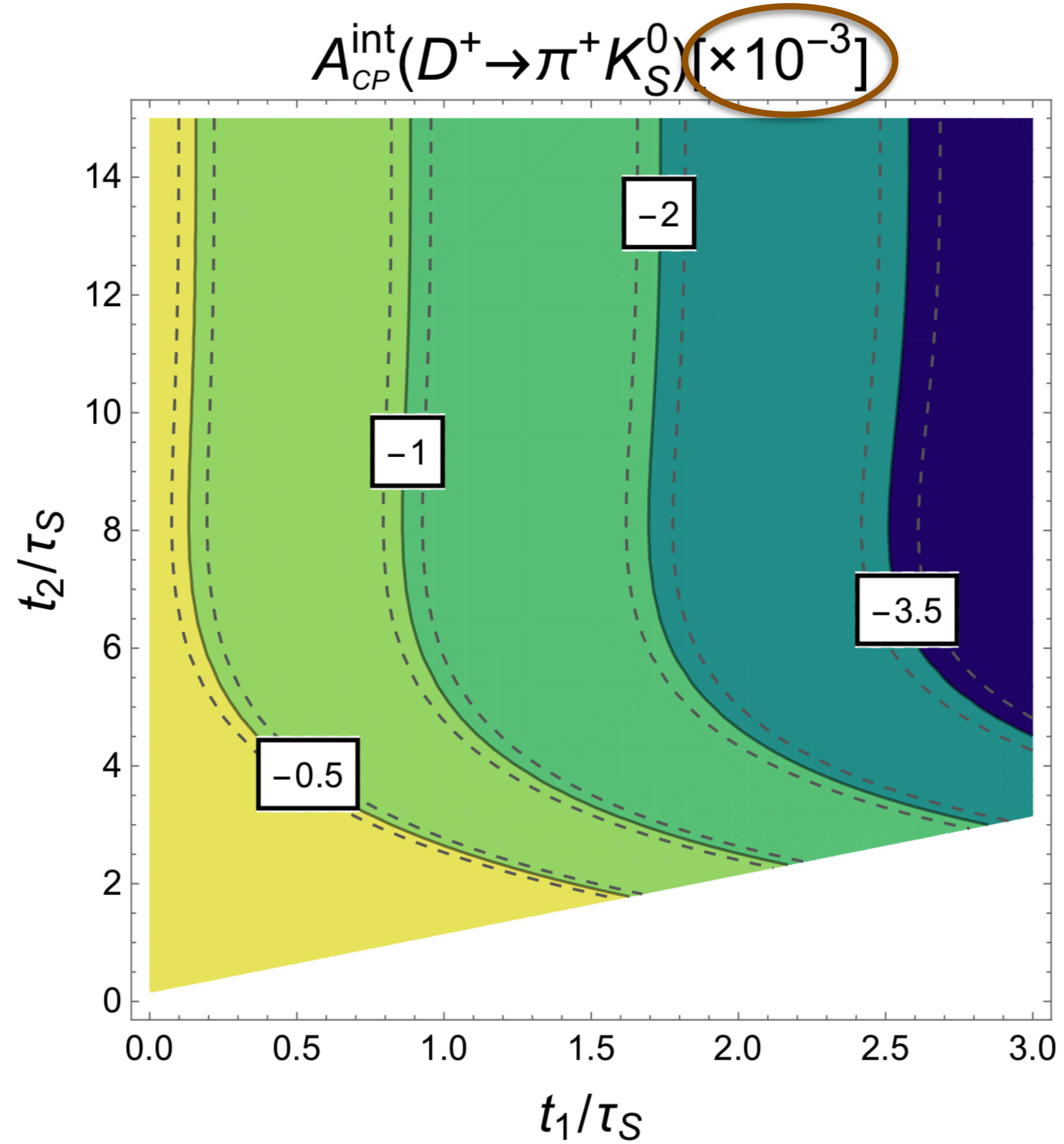


Time-Integrated CPV

total



Interference



Precision in exp: $\mathcal{O}(10^{-4})$

LHCb: $\Delta a_{CP}^{\text{dir}} = (-0.061 \pm 0.076)\%$ @ 3 fb^{-1}

→ **1.2×10^{-4}** @ 50 fb^{-1}

[LHCb, EPJC73,2373(2013)]

CF mode	Yield
$D^+ \to K_S \pi^+$	4.8×10^6
$D_s^+ \to K_S K^+$	1.5×10^6

SCS mode	Yield
$D^0 \to K^+ K^-$	7.7×10^6
$D^0 \to \pi^+ \pi^-$	2.5×10^6

[1406.2624] LHCb @ 3 fb^{-1} [1602.03160]

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^+ \to K_s^0 \pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	±0.03

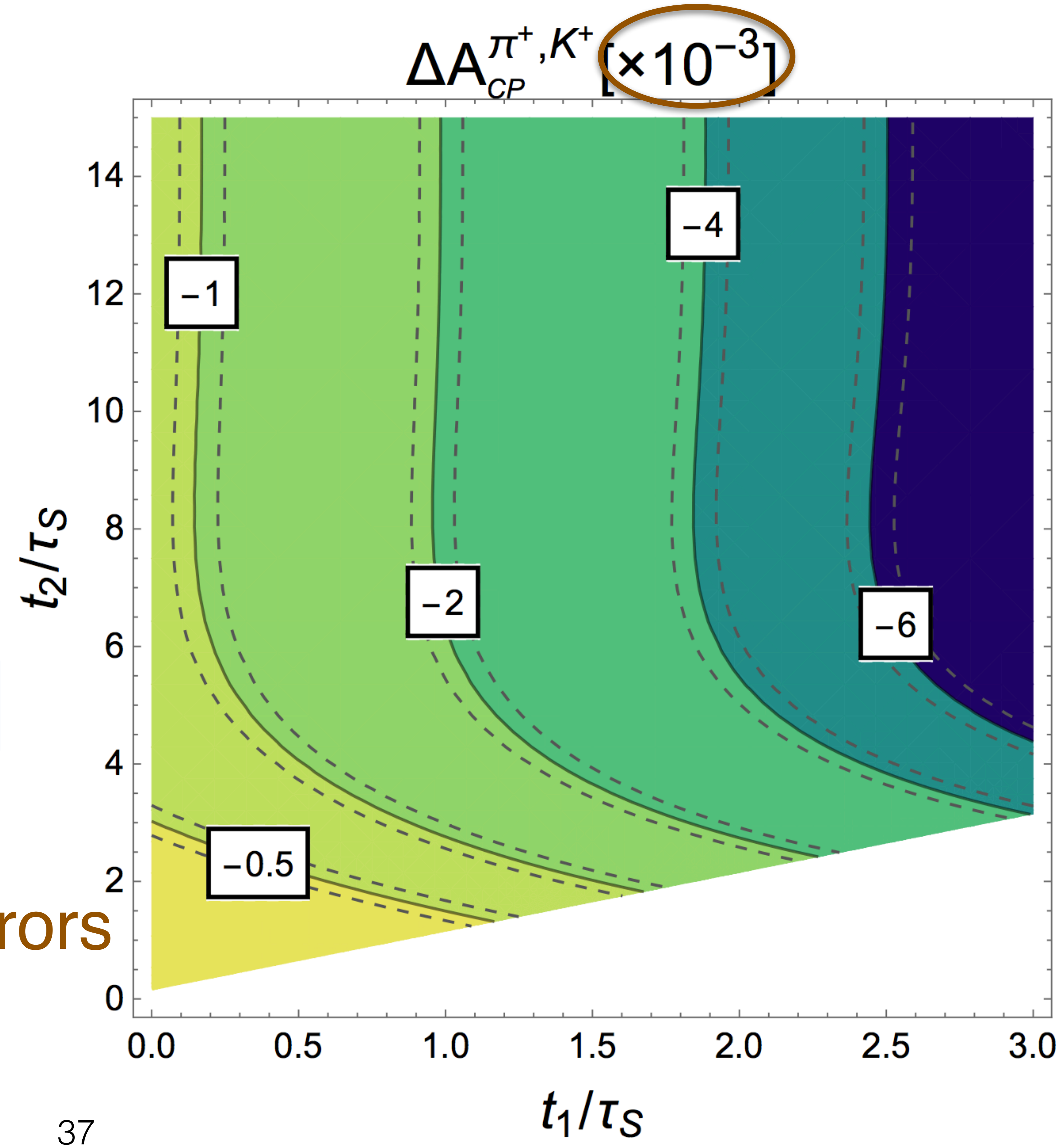
[Schwartz, arXiv:1701.07159]

$$\Delta A_{CP} = A_{CP}(D^+ \to \pi^+ K_S^0) - A_{CP}(D_s^+ \to K^+ K_S^0)$$

New Observable

revealing
new CPV effect

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t) \right]$$



Cancel some systematic errors
@ LHCb & Belle-II

[Wang, **FSY**, Li, ’17]

Advantages — $A_{CP}(D \to K_S f)$

1. **Less ambiguities. Only tree diagrams**, easily established in theory, extracted from Br's. **Compared to SCS processes with penguins.** FAT approach works well.

- In the SM, we don't know how large Acp is in SCS, but we do know it in CF and DCS.

2. **More clear to signal NP.** NP may have large CP phase

Advantages — ΔA_{CP}

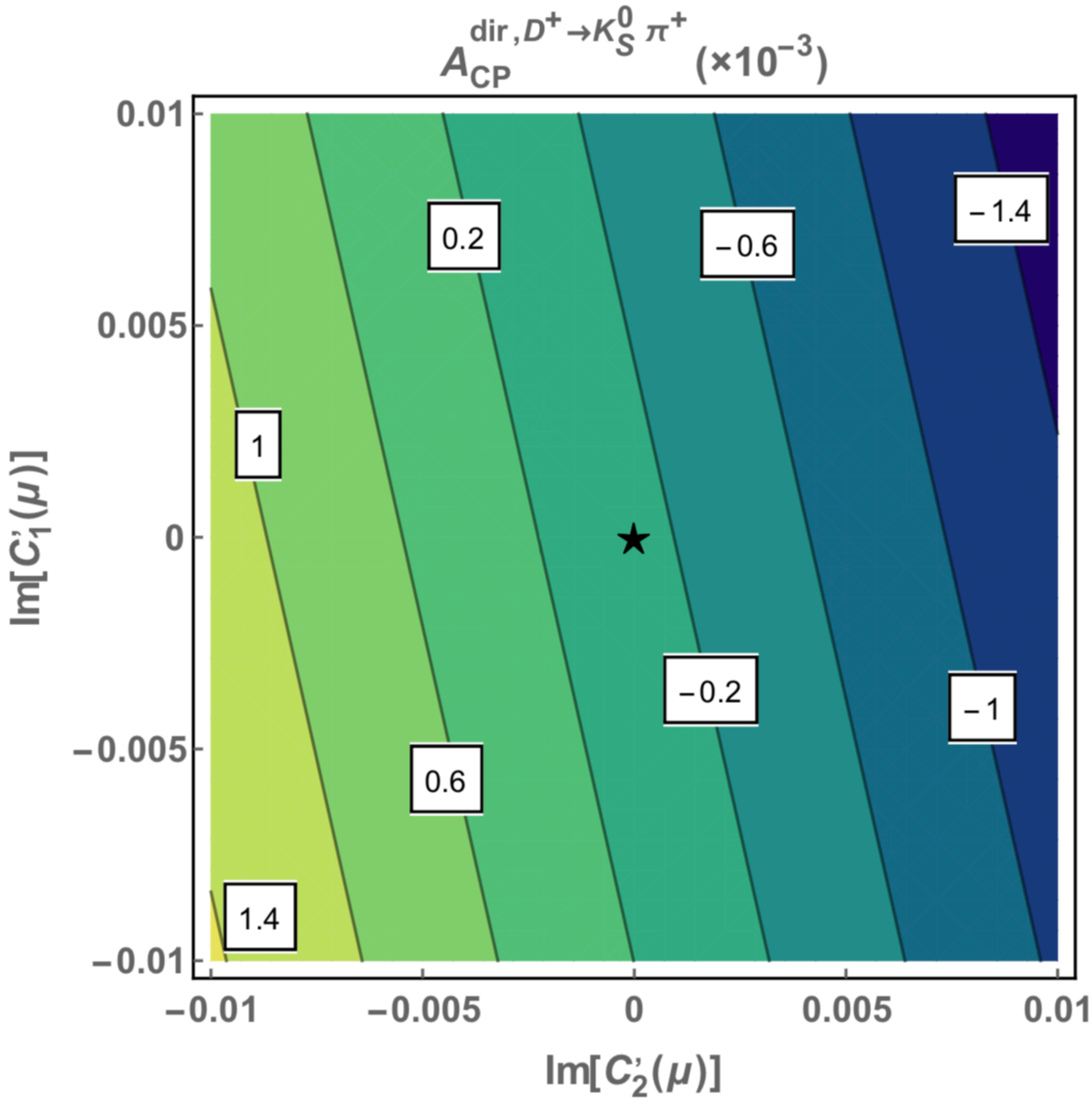
3. Signal CPV in charm. $A_{CP}(K^0)$ cancelled

4. Order of 10^{-3} in SM, accessible by experiments in the near future

5. CPV is doubled in ΔA_{CP}, compared to individual A_{CP}

6. Large branching fractions to measure. CF processes.

7. Some systematic uncertainties cancelled

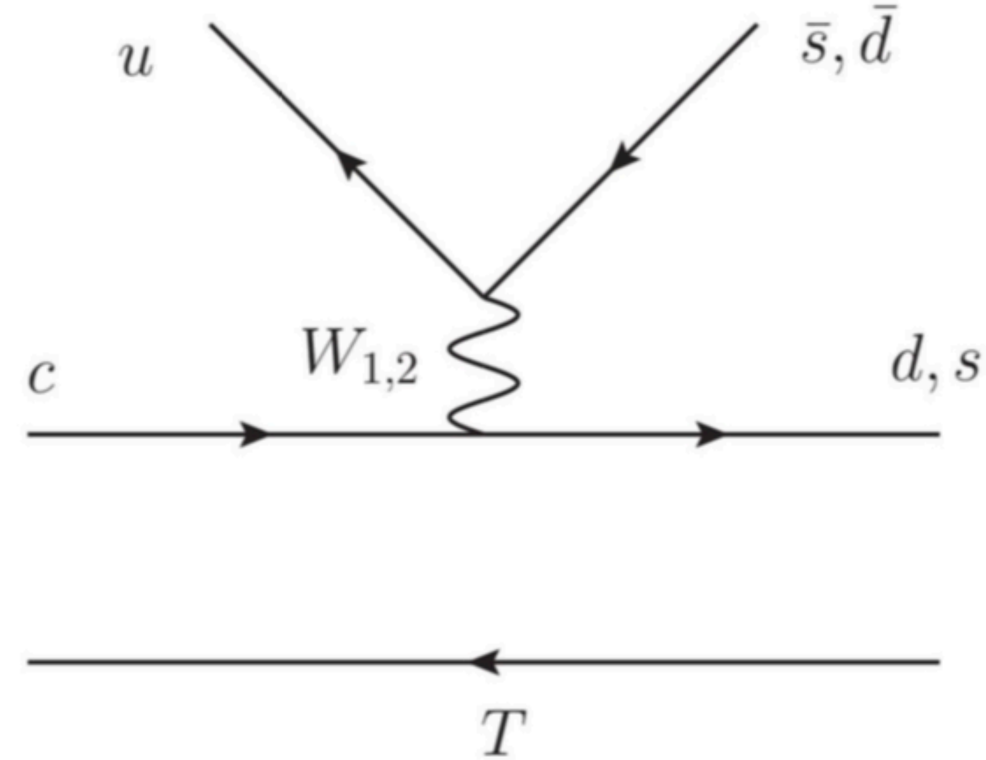

$A_{CP}^{dir, D^+ \to K_S^0 \pi^+}$ ($\times 10^{-3}$)
0.2
−0.6
−1.4
1
−0.2
−1
0.6
1.4
0.01
0.005
0
−0.005
−0.01
−0.01
−0.005
0
0.005
0.01
Im[$C_1'(\mu)$]
Im[$C_2'(\mu)$]

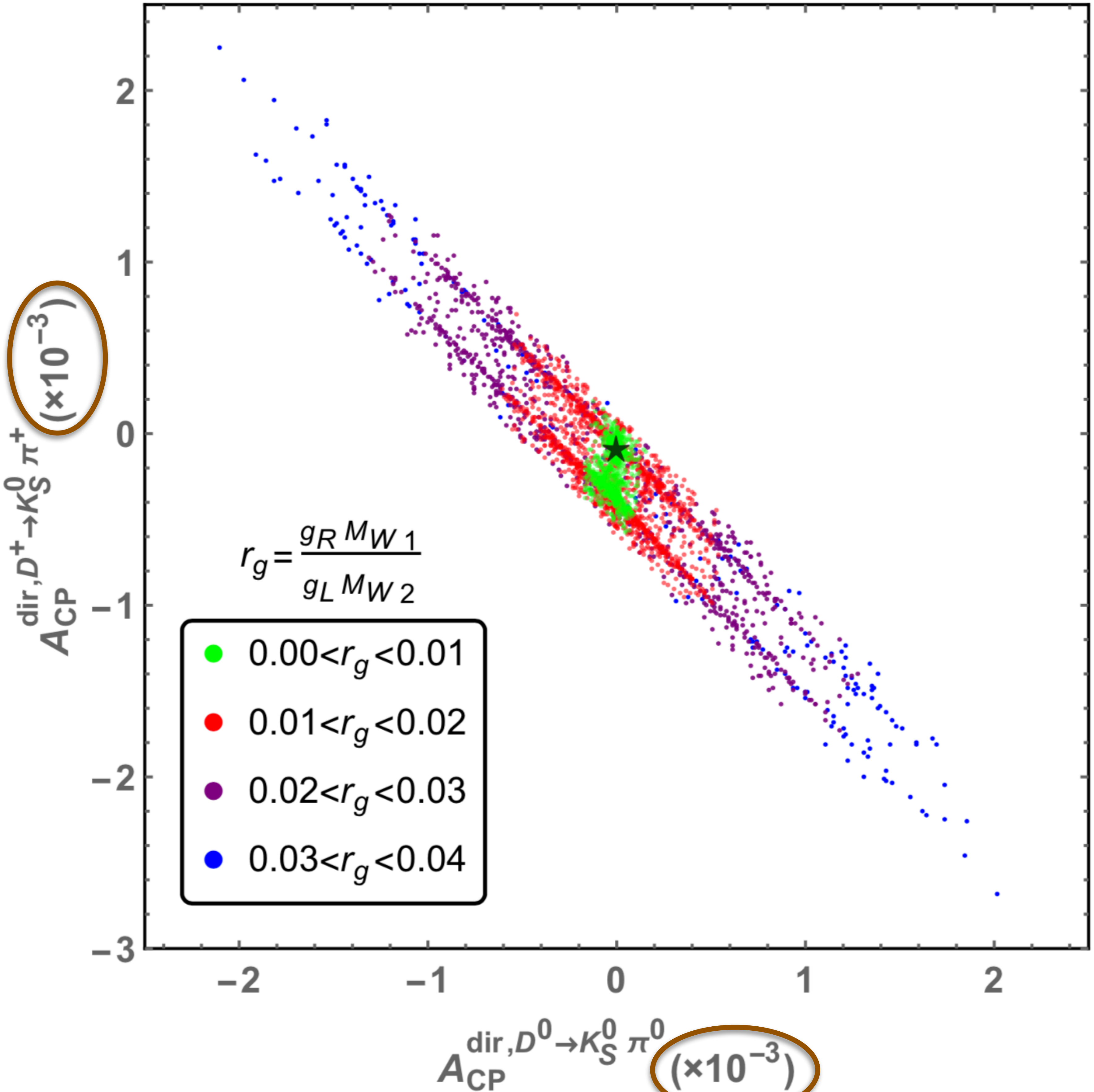
Left-Right Symmetric Model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y$$

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta e^{iw} \\ \sin\zeta e^{-iw} & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix}$$

$$V_{CKM}^R = \begin{pmatrix} 0 & e^{i\phi_0} & 0 \\ \cos\theta e^{i\phi_1} & 0 & -\sin\theta e^{i(\phi_1-\phi_3)} \\ \sin\theta e^{i\phi_2} & 0 & \cos\theta e^{i(\phi_2-\phi_3)} \end{pmatrix}$$





constrained by ΔM_K, ΔM_{B_d}, ΔM_{B_s}, $|\epsilon|$, $S_{J/\Psi K_S^0}$ and $\phi_{B_s}^{c\bar{c}s}$

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - ✦ New Ω_c states observed by LHCb [PRL118,182001(2017)
    - in $\Xi_c^+K^-$ with $\Xi_c^+ \to pK^-\pi^+$
  - ✦ Ξ_b' and Ξ_b^* states observed by LHCb [PRL114,062004(2014)]
    - in $\Xi_b^0\pi^-$ with $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$
  - ✦ Mass and lifetime of Ξ_b^0 by LHCb [PRL113,032001(2014)]
    - via $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$
  - ◉ Suggested to measure $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ [1703.09086]
- **But its branching ratio not directly measured**

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - Fragmentation fraction $f_{\Xi_b^0}/f_{\Lambda_b^0}$ [LHCb, PRL113,032001(2014)]

$$b \to \Xi_b^0 \quad v.s. \quad b \to \Lambda_b^0$$

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.88 \pm 0.04 \pm 0.03)\%$$

≈ 1 ≈ 0.1 assumption in [PRL113,032001]

→ $f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$

- **But its branching ratio not directly measured**

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
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≈ 1 ✓ HQE

≈ 0.1 ? assumption in [PRL113,032001]

$$\rightarrow \; f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$$

- **But its branching ratio not directly measured**

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≈ 1 ≈ 0.1 → **=0.35±0.13**

$f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$ *v.s.* $f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.05 \pm 0.02$

[LHCb, PRL113,032001] [Jiang, **FSY**, 1802.02948]

Branching Ratio of $\Xi_c^+ \to pK^-\pi^+$

Precision improvements are required

LHCb

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = -\mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

BESIII

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$$

30% σ

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

20% σ

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

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30% σ

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

20% σ

10^6 events $\Xi_c^+ \to pK^-\pi^+$ @ 3.3 fb^{-1}

[LHCb, PRL118(2017)182001]

PWA can be performed now

PWA calls for 2019 data